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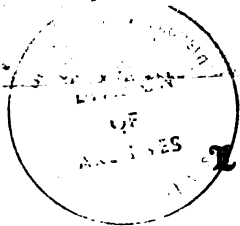
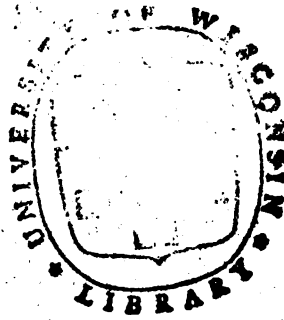
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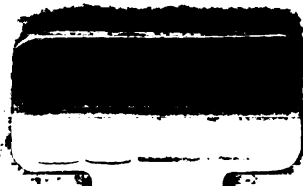
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SPECTROSCOPIC STUDY OF THE
SPARK SPECTRUM IN VARIOUS
GASES.

WILLIAM B. ANDERSON.

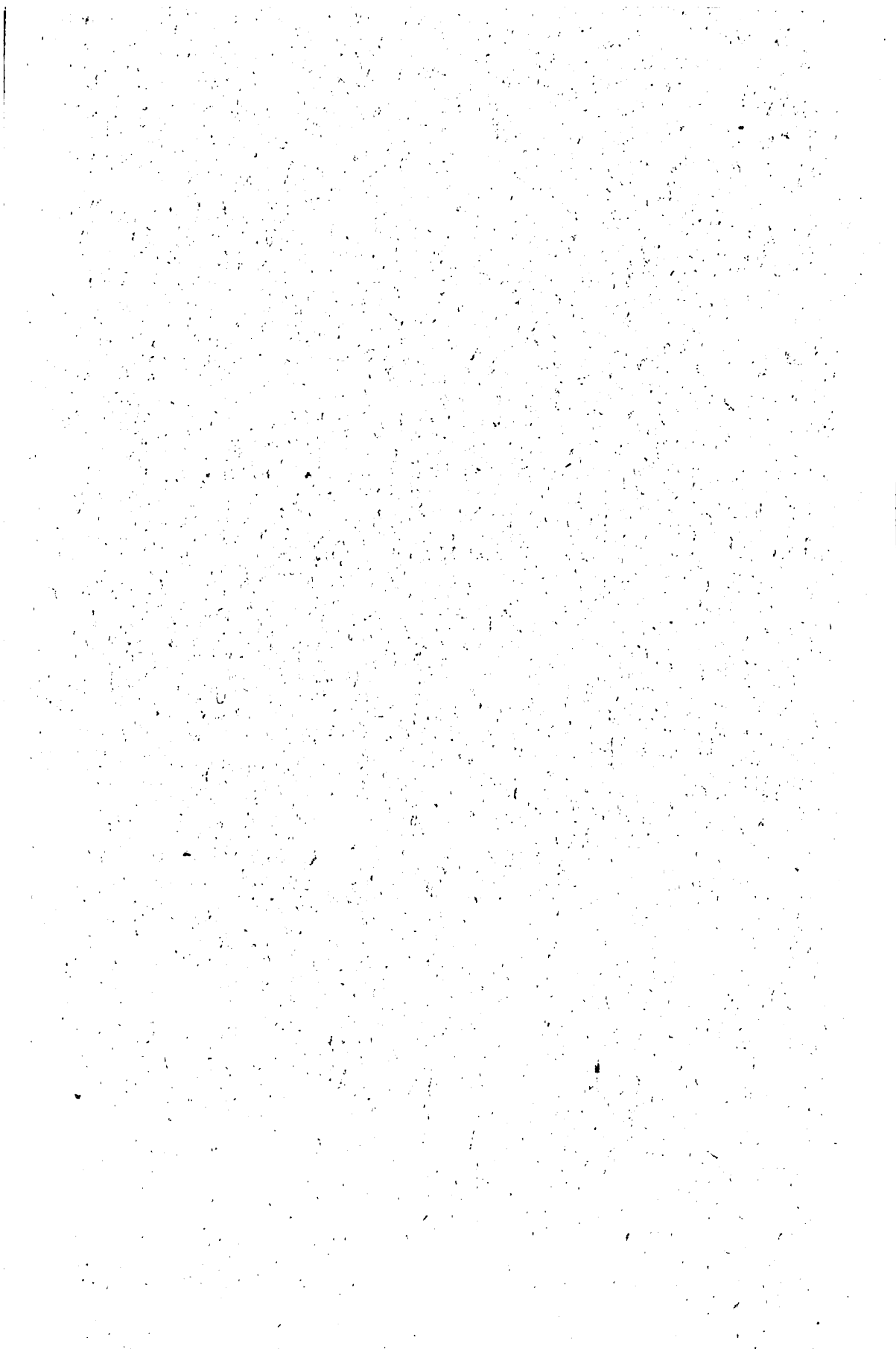


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**A SPECTROSCOPIC STUDY OF THE SPARK
SPECTRUM IN VARIOUS GASES AT
HIGH PRESSURE**

A THESIS

SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF WISCONSIN

1906

BY

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A SPECTROSCOPIC STUDY OF THE SPARK SPECTRUM

By W. B. ANDERSON

In the past decade much study has been given to the changes produced in the spark spectrum by varying some of the quantities connected with the spark or its circuit. This work, however, like the earlier researches, consists of many independent investigations dealing with special phases of the subject and conducted with quite dissimilar apparatus. Naturally, different results were obtained and conflicting conclusions reached. Thus one investigator concluded that the main factor in determining the appearance of the spectrum is pressure;¹ another, vapor density;² another, temperature;³ another, nature of discharge;⁴ another, inductance;⁵ etc. More recent investigators⁶ consider pressure, capacity, and inductance to be important factors; but have varied them, with the exception of pressure,⁷ through small ranges. The observed displace-

¹ See footnote 4, p. 222. Cailletet, *Comptes Rendus*, 74, 1282, 1872.

² Cazin, *ibid.*; 84, 1151, 1877; see also *Phil. Mag.*, 3, 153, 1877; Monckhoven, *C. R.*, 95, 378, 1882.

³ Plücker and Hittorf, *Phil. Trans.*, 155, 1, 1865; Salet, *Ann. chim. et physique* 28, 5, 1873; Secchi, *C. R.*, 70, 79, 1870.

⁴ Stearn and Lee, *Proc. Phil. Soc. Liverpool*, 28, 1874; also *Phil. Mag.*, 46, 406, 1873.

⁵ Hemsalech, *Journal de physique*, 9, 437, 1900.

⁶ Hale, *Astrophysical Journal*, 15, 132, 1902; Hale and Kent, *Ibid.*, 17, 154, 1903; Kent, *ibid.*, 17, 286; Mohler, *ibid.*, 10, 202, 1899.

⁷ Hale and Kent (*loc. cit.*) took spectra at pressures up to 53 atmospheres.

ments of the spectral lines of certain new stars, and Wilsing's¹ idea that these displacements might be due to very high pressure² in the stellar atmosphere, gave the subject added interest.

The present work was undertaken in the hope that some of the questions involved could be answered, and the facts already known correlated, by a study of the effect produced upon the spectrum by separately varying through wide ranges each of the quantities³ connected with the spark or its circuit.

Work upon the spark spectrum may be divided into two parts: (1) the study of change in the width and character of its lines, as well as other changes in its general appearance, and (2) the study of shift, or change of wave-length of its lines. Recent investigations in which spectroscopic apparatus of high dispersive power was used have been mainly concerned with shift, and have discussed rather incidentally the character of the spectrum. The present research deals with both, but principally with the character of the spectrum and its relation to the character of the spark.

The ultimate cause of the above changes in the spectrum cannot consist in changes of capacity, pressure, etc., *per se*, but in resulting changes in the light-emitting vapor. In all probability the appearance of the metallic spectrum depends solely upon the amount, density, pressure, nature, and temperature of the metallic vapor in the spark; and the capacity,⁴ pressure, etc., are of importance only in so far as they affect these conditions of the vapor. The quantities (capacity, etc.) have been varied through the ranges given in Table I, and it has been found that the changes thereby produced in the spectrum may be explained from the above standpoint. Thus the relation between the separate effects of these quantities is shown. It was thought that the potential-drop over

¹ *Astrophysical Journal*, 10, 113, 1899.

² Humphreys and Mohler had previously shown (this *Journal*, Vols. 4, 5, and 6, 1896-97) that when the arc is surrounded by a gas at high pressure, its spectral lines are given slight displacement (shift) toward the red relatively to those of the normal arc.

³ See table, p. 223.

⁴ In all work at pressures above one atmosphere, the *spark* whose spectrum is being studied takes place between insulated *electrodes* in a *spark chamber* filled with a *gas* under pressure. In this spark circuit there is usually a certain *capacity*, *inductance*, and *resistance*. In this paper the above italicized words will always be used in the above sense, unless otherwise stated.

the spark, the current through it, and the energy developed in it, as well as the resistance of the spark circuit (quantities not previously measured in such work), might be closely related to the character of the spectrum. Accordingly these, too, were investigated.

Since much of the apparatus and all the instruments were made especially for use in the work, a somewhat detailed account of these will precede the discussion of results.

TABLE I

Quantity	Range	Ratio. (Of Max. to Min.)
Pressure.....	1 to 100 atmospheres.	100
Capacity.....	0.00145 to 0.2231 microfarads.	150
Inductance.....	0.0135 to 140 milhenrys.	10,400
Potential-drop.....	2000 ? to 12,000 volts.	6 ?
Nature of gas.....	Air, Hydrogen, CO_2 .	
Energy in secondary.....	4, or less, to 125 watts.	30
Resistance.....	0.2 ohms plus spark to 78 ohms, plus spark.	100 ?
Exposure time.....	8 seconds to 10 minutes.	75
Oscillation period.....	1.03×10^{-6} to 1.1×10^{-3} seconds.	1000

APPARATUS

Arrangement.—The arrangement of the apparatus as used is shown diagrammatically in Fig. 1. *T* is the transformer; *C*, the

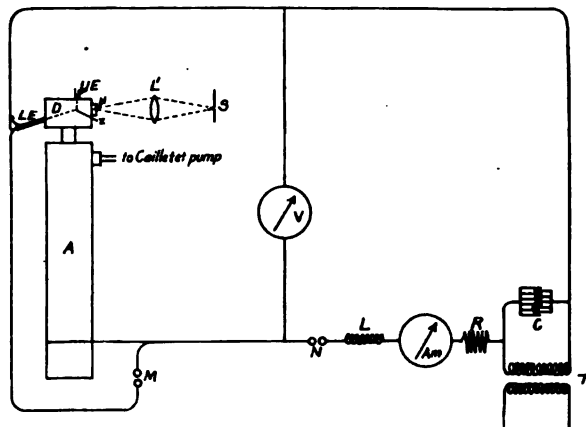


FIG. 1.—Arrangement of Apparatus.

capacity; *L*, the inductance; *R*, the non-inductive resistance (used in only a few cases); *Am.*, the hot-wire ammeter used to measure

the current through the spark Z that takes place between the carefully insulated electrode $L. E.$ and the adjustable uninsulated electrode $U. E.$; V , the static voltmeter¹ for measuring the potential-drop over the spark Z . The light from this spark, which may be called the working spark, passes through the heavy glass window H of the steel compression chamber D , and is concentrated by the lens L' upon the slit S of a Rowland concave grating² spectroscope. The adjustable spark-gap N is sometimes used to maintain the disruptive character of the discharge. A similar spark-gap M , in parallel with the working spark, serves to protect the insulation of the lower electrode $L. E.$ from excessive potential differences. R , L , and C can each be varied through wide ranges or thrown out of the circuit entirely.

Compression tube and compression chamber.—To avoid being limited to the pressures obtainable from ordinary commercial gas cylinders, a special form of tube A and attached compression chamber D was made as shown in Fig. 2. As water from the Cailletet pump is forced into tube A at s , mercury is driven from the annular space C into tube B , thereby forcing the gas from B through u (controlled by valve a) into the spark chamber D . If still higher pressure in D is desired, the valve a may be closed and B may be refilled with gas (usually at about 10 atmospheres pressure) through orifice b , which is controlled by a valve c (not shown) similar to a . This additional gas is then also forced into D as before.

The glass window H , protected by a lead washer on each side, is tightly held on D by the screw-cap I . Lead washers are used at all joints not exposed to mercury. For other joints leather or rubber washers are used.

When hydrogen was used it was generated with an ordinary $Zn-HCL$ generator and collected in a large tank, from which it was pumped through drying-tubes into B . When CO_2 was used it was obtained from a commercial compressed gas cylinder.

Pin valves, consisting of a steel cone screwing down into an accurately ground steel seat, and packed with rubber as shown, were found very serviceable at a and at c (not shown). The elec-

¹ Kelvin vertical quadrant type calibrated from 4,000 to 17,000 volts.

² 14,438 lines per inch, and 21 feet radius of curvature.

trodes *U. E.* and *L. E.* were likewise packed with rubber to prevent leakage. Nevertheless, considerable trouble with leakage was

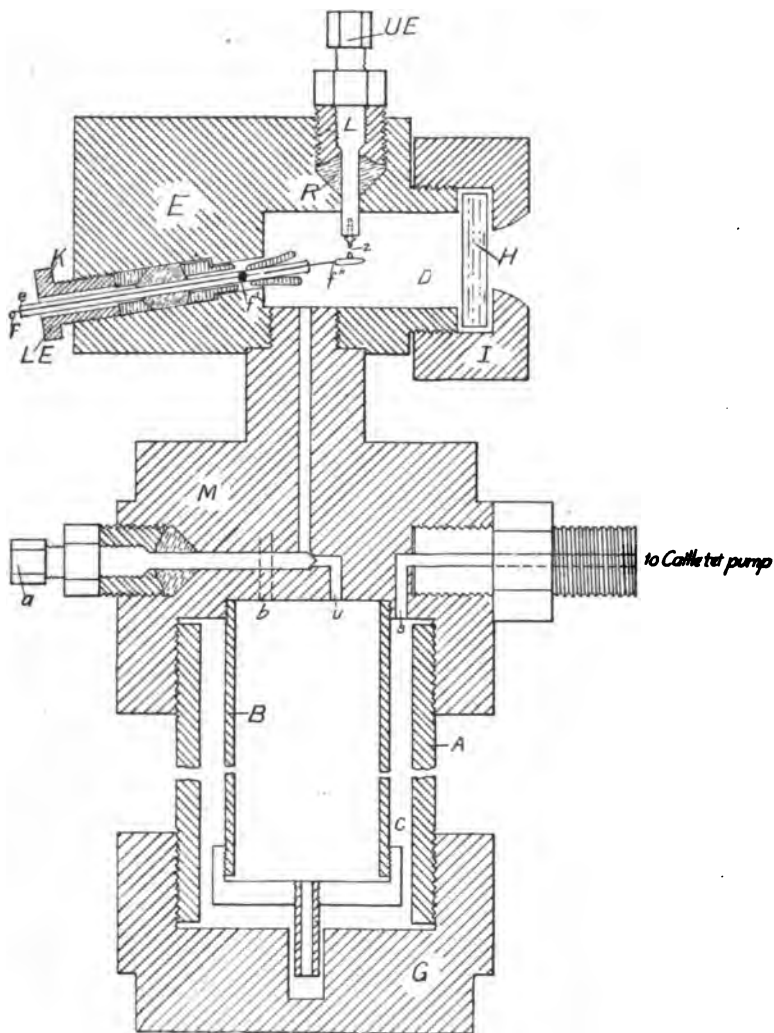


FIG. 2.—Compression Tube and Spark Chamber.

experienced at pressures from 80 to 100 atmospheres, especially with hydrogen.

The electrodes.—The upper electrode, *U. E.*, which is in electrical contact with the compression chamber, can be screwed up or down

to alter the length of the spark-gap and consequently the potential fall over the spark. With larger capacity, and at high pressures, the spark-gap must be very short, or the spark will either not pass at all or else it will pass through the parallel spark-gap *M* (Fig. 1), even though the latter be 6 to 10 mm in length. The intense heat developed under these circumstances readily fuses the electrodes together, while a slight turn of *U. E.* usually separates them so far that no spark passes; thus continual adjustment is necessary. For this reason, what might be termed an hour's exposure really consists of several thousand exposures varying from one-twentieth to one-half second. At lower pressures, say 50 atmospheres or so, the spark often runs steadily for several minutes.

For the lower electrode *L. E.* various forms were tried, and many glass tubes were exploded before one was made that could long withstand the great heat, and the electrical and mechanical stresses. In the final form (*L. E.*, Fig. 2) a copper wire *f* has a short piece of platinum wire tightly fitted into a hole bored in one end. To this platinum wire is fused a small globule of fusible glass, which is then inserted into the tube *e*, and sealed to it at *f'* as shown. With this method of sealing, it will be seen that the gas pressure on the tube is from without, and hence easily withstood. To prevent the wire *f* from locally heating and thereby fracturing the tube *e*, mercury is put in around the wire and kept there by a vulcanite cap (not shown) containing soft wax. This cap is connected with the nut *K* by a vulcanite clamp (not shown), and thus prevents *e* from being forced out by the pressure in *D*. The wire *f''*, making electrical contact with the platinum wire, and hence with *f*, through a drop of mercury in *e*, completes the lower electrode. (*K* to *e* = 3 in.)

The transformer *T* (Fig. 1) has its primary connected with the city circuit of 108 volts and 60 cycles per second. The secondary gives a potential of 15,000 to 20,000 volts, and can furnish a large current, which is necessary when large capacity is used.

The condenser consists of thin (No. 33) sheet brass 9 × 18 in., shel-lacked to glass plates 12 × 22 in. Eighty of these are arranged on edge in an oil tank filled with kerosene of high flashing-point. The brass sheets, properly grouped, are connected with the mercury cups of a switch-board by which the various groups may be con-

nected in parallel or series, and the capacity varied from 0.00145 to 0.2231 microfarads. This condenser is efficient and serviceable, and was built after it was found that the heavy discharges and continuous use burned up the tinfoil and melted the paraffin of a tin-foil-on-glass condenser incased in paraffin.

The variable inductance is composed mainly of 2,000 ft. of No. 14 rubber-covered wire. By connecting to different terminals, inductances from 0.14 to 140 milhenrys are obtained. For smaller inductances special coils were used.

Non-inductive resistance.—Since resistance causes a damping of the oscillations, and may even altogether prevent them, it seemed important to study its effect upon the spectrum. To avoid simultaneously introducing considerable inductance, this resistance is made nearly non-inductive by using high resistance (IA) wire which is wound back and forth over two rows of pegs about 4 inches apart. Computation gives 0.03 milhenrys for the 78 ohms resistance.

The ammeter.—In the hot-wire ammeter shown in Fig. 3 a strip of sheet brass, D , $0.5 \times 5 \times 500$ mm, stretched between the binding

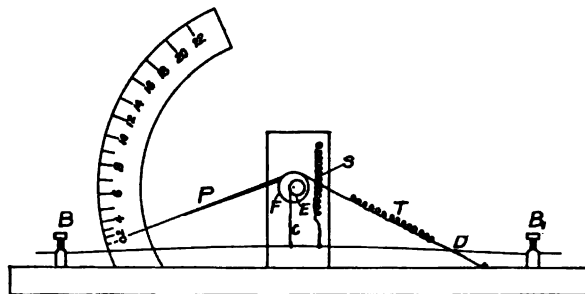


FIG. 3.—Hot-wire Ammeter.

posts B , B_1 , carries the current. As the current heats this strip it elongates, and the spring s contracts, thus permitting spring T to rotate F and thereby raise the pointer P , at the same time winding the thread C upon the eccentrically placed pulley E . E was so placed as to give a fairly uniform scale, as shown. This instrument was calibrated from 2 to 22 amperes, while a similar one with a smaller conductor was used for currents from 0.25 to 5 amperes.

The wattmeter.—Various devices were tried for ascertaining the amount of energy developed in the spark. In the first, immediately

after taking the spectrum, the spark, having all other conditions connected with it kept unchanged, was made to take place inside a special calorimeter. From the rate of temperature rise of the calorimeter, the watts developed by the spark could be computed. However, the spark as used occurred in a gas at high pressure (in the spark chamber), while in the calorimeter it occurred in air at one atmosphere pressure. This makes a great difference in the amount of energy developed, so this arrangement was abandoned.

The spark calorimeter was next used simultaneously with the working spark, and in series with it. This insured the same current in each spark; so that the energy in each was proportional to the potential drop across it. Uncertainty as to the measurement of these potentials was here a fatal objection.¹

Finally the compression chamber itself was made to serve as spark calorimeter, and was calibrated as a wattmeter. For the calibration a spiral of wire heated by a direct current, and using a measured number of watts (say 16.5) was placed in the compression chamber, and temperature² readings were taken every minute. Curve *A*, Fig. 4, is obtained by plotting these temperature readings as ordinates and the corresponding times as abscissae. The other six curves were obtained in the same way. In all cases the calibration was begun with the chamber at room temperature; so this temperature was used as an arbitrary zero in plotting.

To illustrate the use of these curves, suppose in 20 minutes the spark were to heat the spark-chamber from room temperature to 12° above. The point whose abscissa is 20, and whose ordinate is 12, is about half-way between curves *B* (19 watts) and *C* (31.3 watts); hence about 25 watts would be the power expended in the spark.

Though the compression chamber radiates heat freely, and also imparts it to the compression tube by conduction, errors from these causes are eliminated because the same heat losses occurred during the calibration. Indeed, for fifteen or more watts, it seems to be a sufficiently sensitive and accurate wattmeter. The fact that the

¹ See multiple spark-gap, footnote 3, p. 231.

² The thermometer was inserted into a hole bored into the wall of the compression chamber and containing some mercury to make good thermal connection.

curves produced cut the x axis within 20 or 30 seconds of the origin, and also that after breaking the circuit (as at z , curve F) the indicated temperature reaches a maximum in less than a minute, show that the heat is quickly transmitted from the spark to the thermometer.

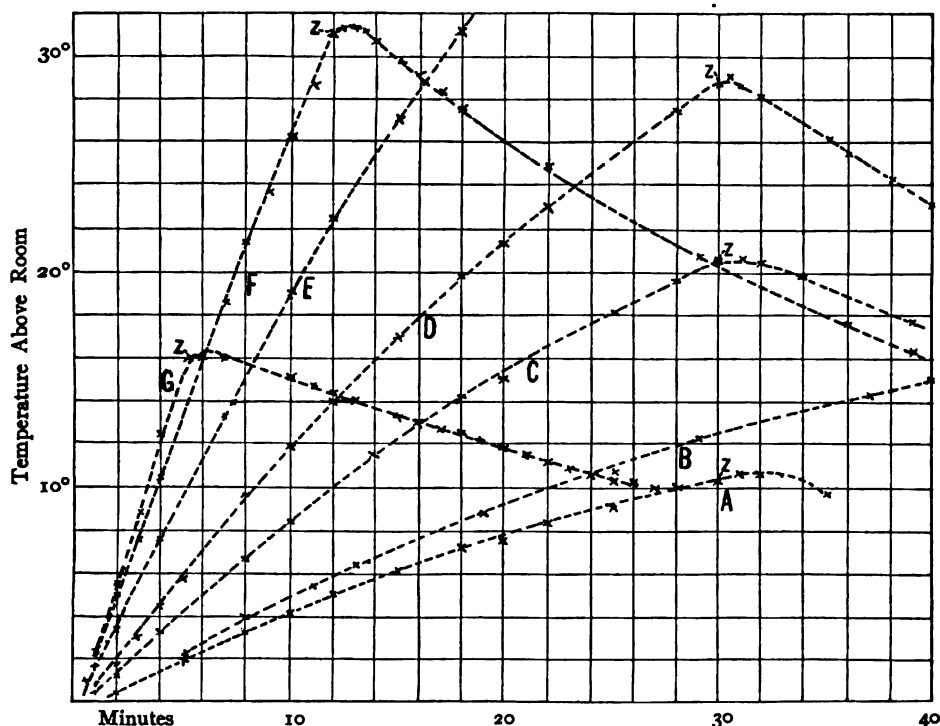


FIG. 4.—Calibration of Spark-Chamber as Wattmeter.

Z marks the point where the circuit was broken.

A=16.5 Watts; B=19; C=31.3; D=47; E=70.5; F=100; G=112 Watts.

The camera.—The camera, of the usual form for gratings, may be raised and lowered, by which motion, and the use of a suitable screen, a dozen or so spectra may be taken on the same plate (see No. 174 and footnote 2, p. 235). This method can be used in comparing the general appearance of the lines of successive spectra as some one of the quantities, capacity, inductance, etc., is varied. To determine shift, the method used by Humphreys and Mohler¹ was adopted.

¹ *Loc. cit.*, p. 222.

RESULTS

Electrical conditions in the spark.—The true value of the current through the spark, the watts used in it, and the potential-drop over it manifestly cannot be directly inferred from the observed values obtained by the ammeter, the wattmeter, and the voltmeter, respectively, because the current through the spark is flowing a very small fraction of the time. Though the spectrum varies much less with these observed values than with change of capacity or pressure, etc., it is believed that the actual values of the current and energy during the brief intervals that the current flows, are of prime importance, and that it is through changes in these values mainly that change of capacity, pressure, inductance, etc., affect the spectrum.

These instruments were calibrated either with direct current circuits or alternate current circuits of moderate frequency. The current and potential variations in the case of the spark are of very high frequency and are also exceedingly irregular; so that direct comparison between measurements of them and those of low frequency cannot be made without serious error.

As this is, to my knowledge, the first attempt¹ at measuring the current, the potential-drop, and the energy of the spark in such work, I shall endeavor to interpret the readings obtained by showing to what extent the various actual values² of the current, the potential, etc., contribute toward producing the observed deflections. This can be best shown by curves.

In Fig. 5, curve I is intended to represent the current in the secondary of the transformer; while curve II, it is believed, represents the potential-drop over the spark, which is practically the potential difference between the needle and the quadrants of the voltmeter. Although the condenser when fully charged produces an opposing *E. M. F.* of several thousand volts, the inductance of the secondary of the transformer (80,000 turns) is too great to permit of sudden variations of the current; so that curve I should be a nearly smooth sine curve as shown.

¹ Battelli and Magri (*Phil. Mag.*, 5, 620, 1903) in an investigation of the oscillation period measured the potential and the energy of the spark in air at one atmosphere.

² Mean square values for various intervals in each cycle.

With curve II, suppose at the time represented by a_2 , the condenser is completely discharged. The value of the current at that instant is aa' , which rapidly charges the condenser to a potential $b_2b'_2$, whereupon the spark-gap breaks down and a group of oscillations follows. For several oscillations the potential-drop over the condenser is but little less than $b_2b'_2$, but the drop over the spark is a small part of this (as shown), because the inductance of the spark is very small compared with the total inductance, and because

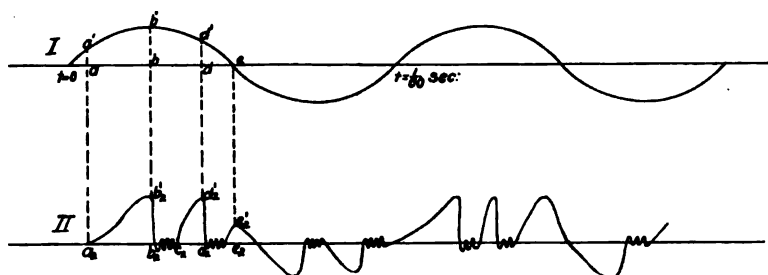


FIG. 5.—Curve I: Current in the Secondary of the Transformer.
Curve II: Corresponding Potential-drop over Spark.

its resistance during oscillations also is probably very small (p. 233). These oscillations continue from b_2 to c_2 ,¹ after which the above cycle is repeated.² At e_2 the condenser is not charged to the sparking potential, and, as the current reverses at e (curve I), no spark occurs until it is charged in the reverse sense to the potential f'_2 . From the curve it is evident how insignificant³ a part the potential

¹ The distance b_2c_2 is greatly exaggerated in the curve. From photographs of the oscillations obtained by the use of the rotating-mirror method and from other calculations, it seems that ordinarily the oscillations last about 1/100 of the time; i. e., $b_2c_2 = 1/100 b_2d_2$, roughly.

² Here the special case has been taken in which the secondary of the transformer furnishes in one-half cycle (1/120 sec.) enough electricity to charge the condenser twice to the potential required to break down the spark-gap. From the photographs of the spark taken with a rapidly moving plate this number was found to vary from one to twelve or more and to be different even for successive half-cycles.

³ In some allied work seven brass knobs, placed in a row and separated by millimeter spaces, were used as a spark-gap. It was found that the potential over four of these sparks (exclusive of the two end ones), instead of being 4/6 of the total, was quite too small to be measured or even detected. Doubtless this was due to the fact that only from b_2 to c_2 (i. e., during oscillations) was there any potential-drop over the voltmeter, except through slight charging by the streamers that precede the spark.

during the interval b_2c_2 , contributes to the resulting deflections of the volt-meter needle, and hence how hopelessly masked its value is.

It is just at this time, too, when the current is surging through the spark, that the potential-drop over it might be most expected to affect the spectrum. The potential read is probably about two-thirds the discharge potential¹ $b_2b'_2$ (see curve II).

This discharge potential may affect the character of the light in three ways. First, through disintegration of the electrodes by the enormous potential gradient,² particles may be thrown into the spark and by their momentary incandescence form the continuous spectrum. Second, through the effect the initial electrostatic stresses may have upon the light-vibrations, if they result from direct electrical action and not from heat. My results throw no light upon this question, but I simply suggest the possibility of such effects.

The third way, through its effect upon the initial discharge, is discussed on p. 248.

The hot-wire ammeter (Fig. 3) integrates the instantaneous values of C^2R , C being the current through the brass strip D , and R its resistance. Evidently the current is practically zero except during oscillations, i. e., from b_2 to c_2 , curve II; so that during these brief intervals, which probably constitute about 1/100 of the time, the current must be very strong to produce as great heating effects as were observed.

Some computations as to the probable current, potential-drop, watts, and resistance of the spark when taking spectrum No. 71c will be given. This particular case is chosen because many other spectra were taken under conditions not greatly different. The indicated current was 20 amperes, voltage, 7,000. (See No. 71c, Table II.) To produce this heating effect with an intermittent current flowing 1/100 of the time requires of course $\sqrt{100} \times 20$ or

¹ I find this estimate in accord with the discharge potentials given by Battelli and Magri (*loc. cit.*, p. 230) for various spark-lengths. Of necessity, since their work was at one atmosphere, I compare the length of their spark ("explosive distance") with that of the parallel spark M , (Fig. 1), which was so adjusted that the spark occasionally took that path.

² Judging from the slight motion (p. 226) of the electrodes required to short-circuit the spark at pressures from 80 to 100 atmospheres, it seemed that the spark-gap was less than 0.05 millimeter. With 10,000 volts over the spark, the potential gradient would then be more than 2×10^6 volts per centimeter.

200 amperes.¹ Again from the capacity, voltage, and frequency, we obtain by computation (as on p. 243) 218 amperes.

Both of these values of the current are necessarily rough approximations because of the uncertainty (1) as to the fraction of the time that the oscillations exist, and (2) as to the value of the charge on the condenser during these oscillations. The current, however, is very probably between 100 and 200 amperes in many cases.

The wattmeter (calorimetric—see p. 228) probably gives the average value of the watts within 10 per cent. More energy is radiated through the glass window of the compression chamber by the spark than by the hot wire with which the calibration was made, but this is a small fraction of the energy in either case, so that the error introduced is slight.

When taking No. 71 (see above), the wattmeter indicated about 100 watts. Assuming the oscillations to persist 1/100 of the time, the average value of the watts during oscillations is 10,000, which with 200 amperes would require 50 volts drop over the spark, showing the resistance of the spark to be 0.25 ohm. This is a very low resistance,² but the spark is exceedingly short, and the great amount of energy in it must develop considerable metallic vapor.

The aim has been to vary, one at a time as far as possible, the quantities given in Table I, and study the changes thereby produced in the spectrum. The capacity, inductance, resistance, and pressure may be varied independently; but the current and energy depend very much upon these values and upon the amount of energy furnished to the primary. Indeed, I believe the effect produced upon the spectrum by varying the capacity, inductance, and resistance is due almost entirely to the resulting change in the energy of the spark, which in turn determines the amount of metallic vapor present. We may then consider pressure, capacity, inductance,

¹ This is without taking into account the increase of R due to "skin effect" (see Drude's *Physik des Aethers*, p. 245). Adapting the formula (Rayleigh's $R = R_0 + \pi r \sqrt{\frac{\mu \sigma}{\tau}}$) which is designed for round conductors, to apply to the brass strip (D) of the hot-wire ammeter (p. 227), I find that with the oscillation period used for No. 71, the skin effect just about doubles the resistance. This doubles the heat effect, so instead of 200 amperes it would require but $200/\sqrt{2}$ or 140 amperes.

² Battelli and Magri, *loc. cit.*, p. 230, obtain less than an ohm for very much longer sparks (at one atmosphere pressure).

resistance, potential-drop (i. e., length of spark) as the independent variables; and current, energy, and oscillation period, as the dependent variables. The energy and also the current may, however, be varied by varying the energy in the primary of the transformer (see No. 91, Table II), leaving the above independent variables unchanged.

In studying the effect of each quantity, fifteen or twenty spectra have, as a rule, been taken; so that it is believed that errors arising

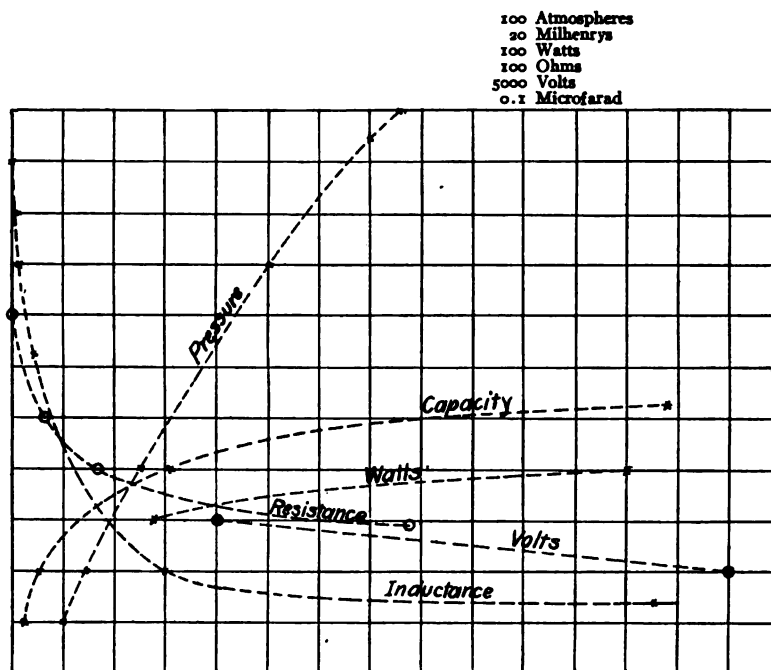


FIG. 6.—Ordinates: Widths of Lines (arbitrary scale).

Abscissae: Pressure, Capacity, Inductance, etc. (on different scales).

from accidental variations have been avoided. In Fig. 6, several curves have been plotted having relative width of reversed lines as ordinates and the corresponding values of the given variable for abscissae. The ordinates are plotted to a different (arbitrary) scale for each curve, since in separately studying the effect of each variable, it is obvious that nothing would be gained by having the scale uniform. The relative widths are averages based upon estimates from several

lines in each case. Frequent references to these curves will be made in the following pages.

Effect of pressure.—The general effect of increase of pressure¹ is to cause the bright lines to increase in width, then reverse, and finally disappear entirely, leaving only, or mainly, reversed lines on a strong continuous spectrum. This is shown, for example, in No. 170,² in which the pressure (see pressure-curve, Fig. 6) is varied as shown on the margin, while the capacity, inductance, etc., were kept constant (see Table II). This effect has the same trend whether the gas used is carbon dioxide (No. 170), air (No. 48), or hydrogen (No. 85); and also whatever value the capacity, inductance, etc., may have, provided these values be kept constant for the series.

If the capacity is small and the inductance large, the pressure must be much higher to produce as wide lines as if the reverse were true; thus No. 120 *a* (70 atmospheres) has not so wide absorption lines as No. 103 *d* (20 atmospheres). Nevertheless, the pairs Nos. 112*a* and 120*a*, or Nos. 112*b* and 120*b*, or Nos. 112*c* and 120*c*, show that in this case also increase of pressure widens the lines if the capacity and inductance are kept constant. These few spectra demonstrate the necessity for stating all the conditions under which such spectra are taken; and also show how difficult it is to draw any conclusions from many previous researches in which this fact has been overlooked.

In case the lines of the different spectra on a plate—e. g., *a*, *b*, *c* and *d* of No. 170—appear slightly displaced relatively to each other, it must not be construed as shift (i. e., change of wave-length), since it is probably due simply to motion of the camera. To determine shift great care was taken not to jar the camera, and a different method was employed (see pp. 229 and 249).

Effect of capacity.—Increasing the capacity has very much the same effect upon the spectrum as increasing the pressure, as shown

¹ Compare work by Hale and Kent, *loc. cit.*

² Hereafter the spectra will be referred to simply by number, as No. 170*a*, No. 170*b*, etc. The plates, together with the conditions under which they were taken, are given in numerical order in Table II, which also shows, in column 2, where the photographic reproductions may be found, if given.

by No. 112, No. 116, and No. 120, in which capacity¹ alone is varied. No. 112*a* is essentially a bright-line spectrum with but one line (λ 3720.08) reversed; while No. 112*d*, with 60 times as much capacity, has many and very wide reversals—in fact, but two lines that are not reversed. These are $\lambda\lambda$ 3709 and 3765, the middle lines of two similar and interesting triplets. In the latter triplets I find changes produced by capacity and pressure similar to those observed by Hale² with the spark under water. The changes of intensity of the different lines of such a triplet relatively to each other is easily noticed because of the close proximity of the lines; so that they are among the best lines to observe throughout the various spectra.

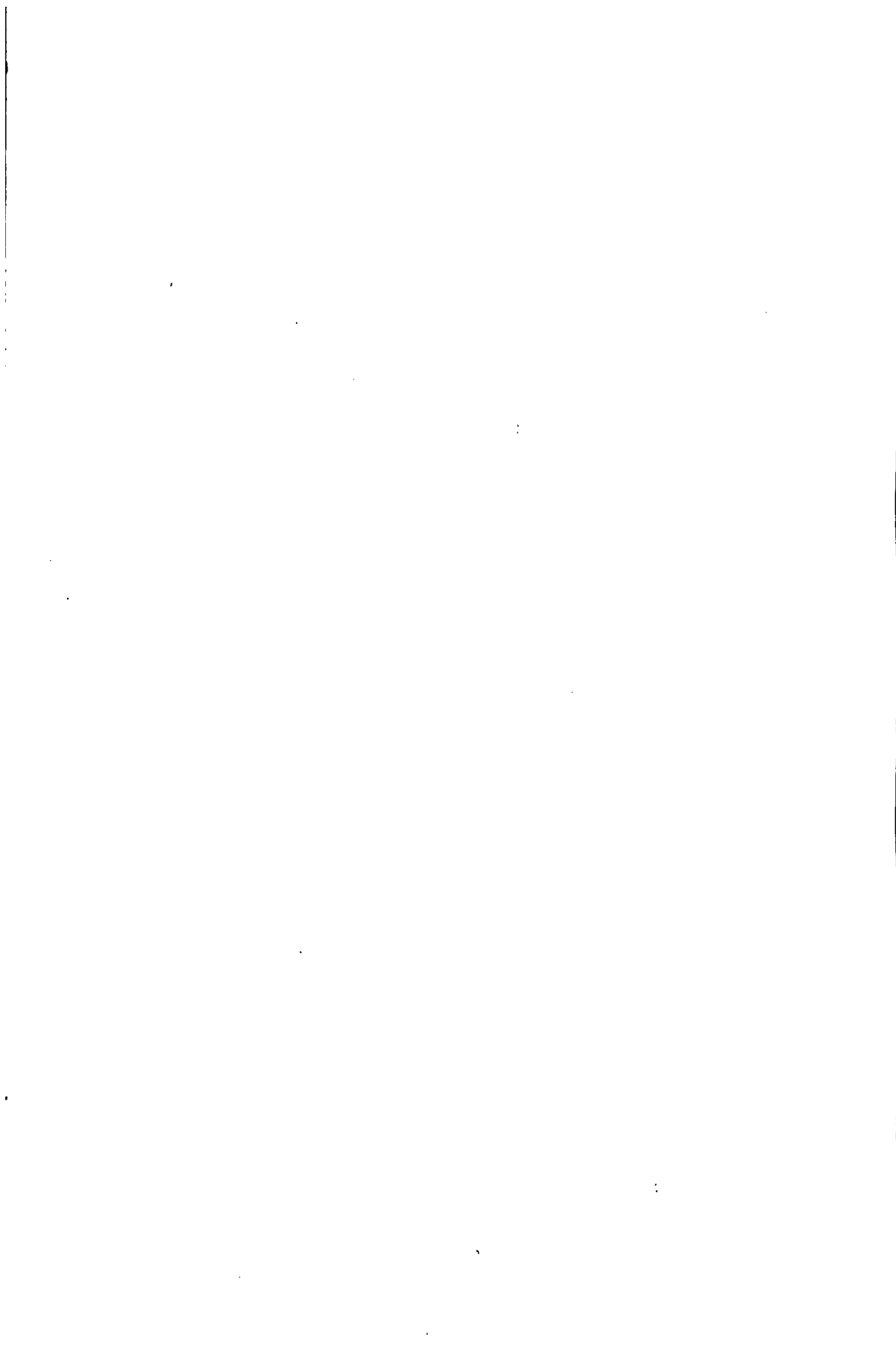
Naming the lines of the former triplet, α , β , and γ (α being λ 3706), their relative intensities may be expressed by 5, 1, and 7, for the arc No. 149*a*); by about the same numbers for No. 174*k* (spark in CO_2 at 1 atmosphere); by 8, 1, and 5, for No. 112*a*; by 5, 1, and 5, for No. 112*b*; and by 1, 1, and 5, for No. 112*c*. β is not reversed in No. 112*d*. γ is, but also shows faintly the bright emission line on each side of the reversal, while α shows no trace of emission line. The intensity of a bright line diminishes very rapidly with increase of capacity (or any other cause of reversal), when the capacity is such as to produce barely perceptible reversal of the line, because the reversal is just at that part of the emission line that would otherwise be most intense. This accounts for the above-cited rapid diminution in intensity of α , which reverses more readily with increase of capacity than does β or γ . The increase in intensity of the middle line relatively to the outer two of the triplet observed by Hale may be explained in the same way. For this middle line (λ 3765.69) has just been shown to be one of the most difficult to reverse in that region of the spectrum. In No. 55, No. 75, and many others α , β , and γ are all reversed, and their relative intensities are about 6, 1, and 4, respectively; while in the solar spectrum (No. 199) they are 2, 1, and 3.

¹ The capacity-curve (Fig. 6) shows the relation between width of lines and capacity change under certain other constant conditions (inductance 140 milhenrys, pressure 50 atmospheres, etc.), and might have a somewhat different form under other conditions. The same may also be said of the other curves.

² *Loc. cit.*

PLATE IV

		3720	3740	3760	3720	3740	3760		
LATE	PRES.							PLATE	RES.
1. 85a	10							No. 63a	78
85b	15							63b	16.9
85c	30							63c	4.69
85d	50							63d	0.25?
85e	70								WATTS
79d	30							91a	27
79e	60							91b	120
79f	25								VOLTS
48a	60							71a	2000?
48b	40							71b	4100
48c	20							71c	7000
170a	50							71d	2000?
170b	40								Exp. Time
170d	15							75a	600
170e	10							75b	120
CAPACITY								75c	20
116a	0.002							75d	5
116b	.0054								
116c	.0309							167a	180
116d	.1286							167b	66
								167c	26
								167d	6
								167e	2
112a	.002							Iron Arc	
112b	.0054							2a	1
112c	.0309							2b	6
112d	.1286							2c	30
								2d	120
								2e	600
120a	.002							IND.	CAP.
120b	.0054							161a	75 0.2231
120c	.0309							161b	23 .073
INDUCTANCE								161c	8.8 .073
55a	0.868							161d	0.7 .0054
55b	.594							161e	0.7 .002
55c	.278							PRES.	GAS
55d	.155							174a	50 CO ₂
								174b	50 H
Pr.	IND.							174c	25 CO ₂
a	50 25.							174d	25 H
b	50 6.5							174e	15 CO ₂
c	20 0.014							174f	15 H
a	40 25.							174g	10 CO ₂
d	20 0.014							174h	10 H
								174i	5 CO ₂



Effect of inductance.—Increase of inductance renders the discharge less violent and produces an effect upon the spectrum directly opposed to that due to increase of capacity or pressure. The reason for this will be discussed later (p. 248). Small variations do not produce a very marked effect (see No. 55); but No. 71c (0.0135 milhenry), and No. 112c (140 milhenrys) are radically different, the latter having several bright lines, the former none. Compare also No. 186 with No. 187.

Effect of resistance.—Resistance affects the spectrum² in the same way that inductance does, as shown by No. 63.

Energy in the spark.—The effect of increasing the energy in the primary from 120 to 720 watts (capacity, etc., kept unchanged), and thereby increasing the energy in the spark from 27 to 120 watts (see No. 91), is similar to that produced by increase of capacity, the absorption lines becoming, in this case, about one-third wider, and the continuous spectrum more intense. This effect is less than was expected (see p. 247).

Effect of potential.—As the potential is increased, by lengthening the spark-gap (see Fig. 2), the lines become slightly narrower (see No. 71), though just the opposite effect² might be expected (p. 248). The lowest potential used in this case is lower than that for which the voltmeter was calibrated, and is therefore uncertain; but this affects the result only in a quantitative way.

Nature of the gas.—In No. 149 several spectra were taken, using alternately air and hydrogen in the spark-chamber at the pressures shown, in order to compare the effects of these two gases.

A similar series (No. 174) was taken to compare carbon dioxide with hydrogen and hence with air. The pair *a* and *b* cannot be directly compared because *b* was much more exposed³ than *a*, and consequently has narrower lines.

Equal exposure for such a series of spectra is very desirable,

² See resistance and inductance curves, p. 234. It will be observed that both these curves are roughly of the exponential type, $y = e^{-x} + b$, in which *b* is the limiting (minimum) width approached as inductance or resistance, *x*, is increased. The capacity-curve is of the form $y = a - e^{-x}$, in which *a* is a limiting (maximum) width of line.

² Perhaps the opposite effect could be obtained under other conditions of pressure, capacity, etc.

³ See effect of exposure, p. 238.

but not easily attained, because different amounts of "smoke" on the compression-chamber window, and various other conditions, cause the proper time of exposure to vary from a few minutes to several hours. A small test-plate, slipped into an attachment at one side of the camera, which could be taken out and developed when it was thought the main plate was sufficiently exposed, was found very useful, but did not completely solve the problem of equal

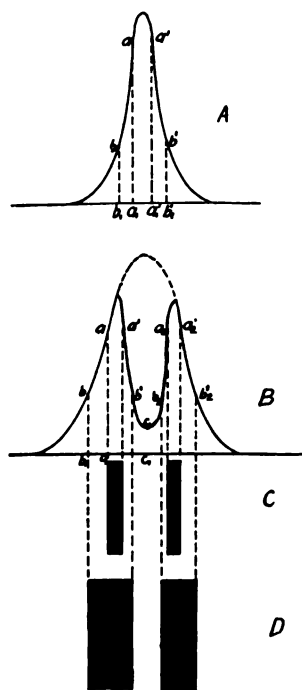


FIG. 7.—Intensity-curve for spectral line.

intensity-curve in the immediate vicinity of a bright line¹ (A, Fig. 7), as given by Rayleigh² and Michelson³. If the time of exposure is so brief that intensities of less value than a, a fail to noticeably darken the negative, a line of width aa' results; whereas a longer

exposures. From these plates, however, from No. 55a and No. 186, and from plates taken for other purposes, I estimate the relative widths of the reversed lines to be 4, 5, and 6, respectively, for air, carbon dioxide, and hydrogen. The spark runs more steadily in hydrogen than in air or in carbon dioxide, which would probably cause more vapor to be produced and hence wider lines.

Duration of exposure.—In some previous work it was observed that the width of the bright lines increased markedly with the time of exposure (No. 2); and it was thought that for the same reason the reversed lines should be narrowed by increased exposure. This is shown to be the case by No. 167 and No. 75. No. 75c (20 sec.) has nearly twice as wide lines as No. 75a (10 min.).

The reason for this change in width is evident from a consideration of the

¹ For a different application of the same idea see Kayser's *Spectroscopie*, II, p. 297.

² *Ibid.*, p. 343; *Phil. Mag.*, 27, 298, 1889.

Astrophysical Journal, 2, p. 251, 1895.

exposure, which enables intensity b, b to darken the negative, gives a line of width bb' .

Similar reasoning will show that if B , Fig. 7, represents the intensity curve¹ for a bright line partly reversed, then the short exposure will give a bright line of width $a_1 a_1$ (aa'_1), having a reversal of width $a'a_2$, as shown by C ; while the longer exposure gives the line shown at D .

Order of reversal.—In general it may be said that certain lines reverse more readily² than others, and that any series of changes that increases the number and width of the reversals, will do so in approximately the same order, whether it be through increase of capacity or pressure, or through decrease of inductance or resistance. There are, however, cases in which the order of reversal seems to differ for some of the weaker lines. For example, No. 143*a* and No. 170*e* (Table VI) have each twenty-seven reversals, but not of the same lines throughout. Duration of exposure might cause such differences; for if certain lines have a relatively high value $c_1 c$ (B , Fig. 7), it will be clear that such intensity will suffice to darken the plate with long exposure so that no reversal occurs, even though with short exposures they do occur.

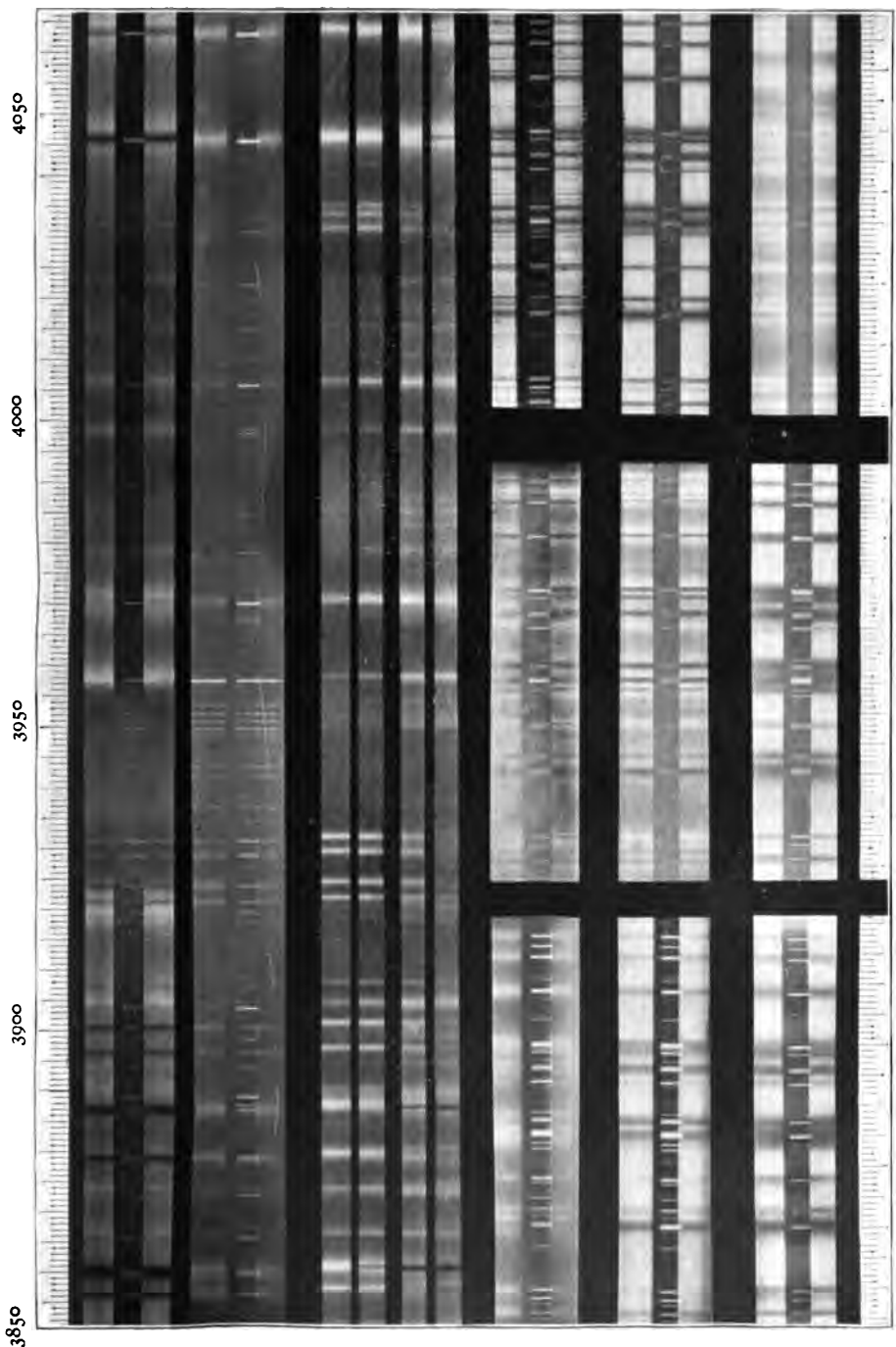
Increase of capacity and pressure tends to reverse more lines and widen those already reversed, while increase of inductance tends to narrow and also to suppress reversals. It appears, however, that capacity and pressure affect most strongly the prominent, easily reversed lines, and inductance, those difficult to reverse. Thus when both capacity and inductance (No. 134 and No. 120*c*), or pressure and inductance (No. 127), or all three (No. 137), are large, the strong lines have very wide reversals, while some of the weaker lines e. g., λ 3765, do not reverse at all. Compare these with No. 186 and No. 103*d* of low pressure and small inductance. No. 137 and No. 103*d* show the most striking difference. In No. 103*d*, λ 3765 shows as a reversed line and is not reversed in No. 137, although in the latter λ 3720 is three times as wide as in the former. I cannot explain this peculiar behavior of the lines. Inductance

¹ See curve by Jewell, *Astrophysical Journal*, 3, 89, 1896; also Kayser's *Spectroscope*, II, p. 360.

² Kayser's *Spectroscopie*, II, pp. 518, 296.

TABLE II

Spectrum: No.	Plate No.	Pressure in Atmos- pheres	Inductance in Mil- henrys	Capacity in Mfd.	SECONDARY			Gas	
					Volts	Am- peres	Watts		
44	V	80	0.0135	0.00152				H	
48a	IV	20						Air	
48b	IV	40						Air	Watts in Prim-
48c	IV	60						Air	ary,
55a	IV	50	0.868	0.0309	5200	5.75	100.0	H	740
55b	IV	50	.594	.0309	5200	—	80.0	H	740
55c	IV	50	.278	.0309	5200	8.0	—	H	
55d	IV	50	.155	.0309	5200	9.0	—	H	Res.in Second-
63a	IV	50	.045	.0309	6800	2.35	4.1	H	ary, 78 ohms
63b	IV	50	.045	.0309	7000	4.5	9.6	H	16.9 ohms
63c	IV	50	.045	.0309	6200	9.5	40.0	H	4.69 "
63d	IV	50	.045	.0309	6200	16.	115.0	H	0.5 "
71a	IV	50	.0135	.0309	2000 ?	18.	70.	H	(leads and
71b	IV	50	.0135	.0309	4100	18.	100.	H	spark)
71c	IV	50	.0135	.0309	7000	20.	90.	H	
71d	IV	50	.0135	.0309	2000 ?	22.	75.	H	
75a	IV	60	.0135	.0309	5000	18.	80.	H	
75b	IV	60	.0135	.0309	5000	—	75.	H	
75c	IV	60	.0135	.0309	5000	—	—	H	
75d	IV	60	.0135	.0309	5000	—	—	H	
79d	IV	30	.0135	.0309	5000	15.	—	H	
79e	IV	60	.0135	.0309	5000	—	—	H	
79f	IV	25	.0135	.0309	5000	15.	—	H	
85a	IV	10	.0135	.00543				H	Watts in Prim-
85b	IV	15	.0135	.00543				H	ary,
85c	IV	30	.0135	.00543	2700	11.5	85	H	520
85d	IV	50	.0135	.00543	—	—	—	H	
85e	IV	70	.0135	.00543	—	—	—	H	
91a	IV	50	3.0	.0388	—	2.8	27.	H	140
91b	IV	50	3.0	.0388	4100	6.8	120.	H	720
95a	IV	40	25.0	.170	—	2.0	—	H	Res.in Second-
95d	IV	20	0.0135	.170	—	16.	—	H	ary, 4.9 ohms
99a	—	50	25.0	.0388	4100	2.7	60.	H	4.9
99b	—	50	0.0135	.0388	4100	22.0	125.	H	
99c	—	50	0.0135	.0388	4100	—	150.	H	
99d	—	50	25.0	.00543	—	1. ?	45.	H	4.9
103a	IV	50	25.	.1286	—	1.5 ?	38.	H	4.9
103c	IV	50	6.46	.1286	—	—	—	H	2.59
103d	IV	20	0.0135	.1286	—	—	—	H	
107a	—	100	25.0	.00543	3200	1. ?	78.	H	4.9
107b	—	100	25.0	.0309	4000	2. ?	58.	H	4.9
107c	—	100	6.46	.00543	3800	2.	68.	H	2.59
107d	—	100	0.0135	.00543	4100	14.	95.	H	
107e	—	100	.0135	.002	4100	10.5	100.	H	
112a	—	50	140.0	.002	—	1.4	55.	H	9.30
112b	—	50	140.	.00543	—	—	30. ?	H	9.30
112c	IV	50	140.	.0309				H	Res.in Second-
112d	IV	50	140.	.1286				H	ary, 9.3
116a	IV	40	140.	.002		1.0	35.	H	9.3
116b	IV	40	140.	.00543		0.45	35.	H	9.3
116c	IV	40	140.	.0309		.4	50.	H	9.3



No. 137

127

1121

1126

1125

112d

127

44

190

No. 199

186

187

No. 127 in H at 100 atmos. Ind. 140. 44 in H at 80 atmos. Ind. 0.0135. Cap. .0015 100 in CO, at 100 atmos. Ind. 0.0135. Cap. .0054	3720	3740	3760	No. 132 in H at 30 atmos. 500 Volts. Fe Arc. 134 in H at 30 atmos. Spark. Ind. 140. Cap. 0.223 137 in H at 70 atmos. Spark. Ind. 140. Cap. 0.223	3720	3740	3760	No. 199 Solar Spectrum 186 in CO, at 53 atmos. Ind. 0.87. Cap. 0.027 187 in CO, at 50 atmos. Ind. 75. Cap. 0.027
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slows the discharge and causes conditions in the spark to approach more those of the arc. But it is just in the arc that numerous but narrow reversals occur (column 2, Table VI). To be sure, in the case of the arc, the briefness of exposure, and the fact that the spectrum is not a composite of numerous spectra as with the spark (p. 245), accounts largely for the more numerous reversals.

Wave-length.—In Plate V a portion of the spectrum toward the region of longer wave-lengths is shown for Nos. 112, 127, and 137. From these, and from the portions of the same spectrum numbers (also Plate V) in the vicinity of λ 3700, it will at once be seen (as many have observed) that the lines of short wave-length, in general, reverse much more readily than those of longer wave-length. As the character of the discharge becomes more disruptive and less like the arc, the lines of shorter wave-length become more prominent, and new "spark lines" appear. This is generally supposed to be accompanied by more intense heat in the spark. The light producing the more readily reversed lines may, then, originate near the center (hottest part) of the spark, and the surrounding vapor causes the reversal, while for the less readily reversed lines, the surrounding vapor is sufficiently hot to give them as bright lines, hence they do not ordinarily reverse (compare Lockyer's "long" and "short" lines of the arc).

Oscillation period.—Not much can be gained by comparing spectra taken with different oscillation periods, for the reason that in changing the period either capacity (C) or inductance (L), or both, must be changed; since $T = 2\pi\sqrt{LC}$. It was thought, however, that with an exceedingly slow period the current would resemble that of the alternating arc, and so might also the spectrum resemble the arc spectrum. Accordingly, a very large capacity and inductance were used, giving a period of $1/900$ second, which does not differ greatly from that of ordinary alternating circuits. Under these conditions No. 133, No. 134, No. 135, and No. 137 were taken at 20, 30, 50, and 70 atmospheres pressure, respectively.

It was next attempted to take arc (500 volts with 100 ohms in series) spectra at these same pressures for comparison, but the apparatus was not well adapted to the use of the arc, so that the best spectrum obtained, No. 132 (30 atmospheres), was hardly good

enough to reproduce. However, by comparing negative No. 132 and No. 134, which was taken at the same pressure but with the spark, it was found that the latter gave somewhat wider lines. The reason for this difference is not apparent, since the value of the current seems to be about 4 or 5 amperes in each case. For with the spark, the frequency multiplied by the capacity in farads (see No. 134, Table II), by the charging potential in volts, and by 4,¹ gives 4.9 amperes;² while from the resistance and voltage used, the current through the arc must have been about 5 amperes. This current was too intermittent to be measured.

Direct comparison of effects.—In some cases two spectra show that the effect upon the spectrum of a change in one variable is just about compensated for by a simultaneous change in another variable. Thus No. 95*d* and No. 95*a* are very much alike, showing that the widening effect upon the lines, caused by doubling the pressure, is balanced by the narrowing effect of increasing the inductance two thousand fold. With one-fourth as much capacity, but seven-fifths as high pressure, No. 120*c* is similar to No. 112*d*. Also the effect of increasing the inductance from 0.045 to 25 milhenrys appears to be offset by decreasing the resistance from 78 to 4.69 ohms, as shown by No. 63*a* and No. 99*a*. No. 161*e* and No. 161*a* show that increasing both capacity and inductance a hundredfold gives two and a half times as wide lines, hence capacity has the greater effect. Other similar cases might be cited, but the relative importance of these various quantities in affecting the spectrum can perhaps be better discerned from certain particular cases of maximum effects.

Maximum effects.—In studying the effect of capacity four different spectra were taken with the four different values given (see No. 116), first at 40 atmospheres, then at 50 (No. 112), then at 70 (No. 120). The inductance for all twelve spectra was 140 milhenrys. These spectra show that for a certain value of the capacity a given percentage change of the variable (capacity) produces a maximum percentage change in the width of the lines. This value of the

¹ The factor four is introduced because the condenser not only discharges but charges again in the opposite sense in one-half cycle.

² Not mean square, but average current during each group of oscillations.

capacity may then be said to be that at which the maximum effect of capacity change occurs (other conditions being as given). With different inductance, etc., this value of the capacity would probably be somewhat different. The percentage change in the variable (e. g., capacity) divided into the resulting percentage change in line-width may be termed α .

In Table III, column 6, the maximum value of α , found in the above way for the different variables is given, and the variable having the largest value for α , namely pressure, may be called the most important variable.

TABLE III

Spectrum No.	Reproduction Plate	Gas Used	Quantity Varied	Relative Width of Reversed Lines	α	No. Reversed Lines	Capacity	Pressure	Inductance
174e	IV	CO ₂	Pressure { 15 Atmosphere	2	2.0	25	0.00543	15	0.0135
174g	—		10	1		8	.00543	10	.0135
143c	—	Air	Pressure { 15 Atmosphere	3	1.0	35	.0309	15	.0135
143b	—		10	2		27	.0309	10	.0135
79e	IV	H	Pressure { 60 Atmosphere	2	1.0	61	.0309	60	.0135
79d	IV		30	1		61	.0309	30	.0135
112b	IV	H	Capacity { .00543	2	0.4	14	.00543	50	.140
112a	IV		.002	1		2	.002	50	.140
120b	IV	H	Capacity { .00543	3	0.2	19	.00543	70	.140
120a	IV		.002	2		7	.002	70	.140
55b	IV	H	Inductance { .58	2	-.11	62	.0309	50	.58
55d	IV		.14	3		69	.0309	50	.14
103a	IV	H	Inductance { 25.	3	-.08		.1286	50	25.
103c	IV		6.5	4			.1286	50	6.5
71c	IV	H	Volts { 2000 ?	3	-.13		.0309	50	0.0135
71a	IV		7000	2			.0309	50	.0135
174d	IV	H	CO ₂	4			.00543	25	.0135
174c	IV			3			.00543	25	.0135
140d	—	H	Air	3			.00543	30	.0135
149c	—			2			.00543	30	.0135
91b	IV	H	Watts { 120	4	.1		.0388	50	3.0
91a	IV		27	3			.0388	50	3.0
63b	IV	H	Ohms { 16.9	4	-.08	61	.0309	50	0.0450
63c	IV		4.69	5		68	.0309	50	.0450
75b	IV	H	Sec. expos'd { 120	$\frac{2}{3}$ to $\frac{1}{2}$			.0309	60	.0135
75c	IV		20				.0309	60	.0135

DISCUSSION OF RESULTS

Having shown the effect of these variables upon the width[†] of the lines, etc., it remains to correlate these various effects by showing

[†] All causes that widen the lines also increase the intensity of the continuous spectrum.

how the energy in the spark depends upon each variable. But the energy in the spark determines the amount, and largely the condition, of the vapor in the spark, which in turn determines the character of the spectrum.

Widening of spectral lines.—I wish first to refer briefly to some hypotheses that have been advanced to account for widening of lines. Among these may be mentioned (1) change of wave-length due to Doppler effect caused by motion of the light-emitting particles¹ (kinetic gas theory); (2) modification of the vibration period due to the presence of neighboring molecules;² (3) limitation of the number of regular vibrations by sudden changes of phase³ resulting from collisions. To these I will add (4) a one-sided widening due to shift caused by change in the average dielectric constant (p. 253).

Of these, (1) is of first importance in rarefied gases, as pointed out by Michelson⁴, and of little importance in my work. For the molecular speeds increase with the temperature, which presumably is not vastly higher in the spark under pressure than in the case of incandescent gases at low pressure, which latter give narrow lines. The other hypotheses would account for the great increase in the width of the lines through the crowding together of the molecules as the pressure, or the rate of generation of the metallic vapor, is increased. Especially important in the present work seems (3), by which Michelson has been able to account fairly well for the widths he obtained experimentally.

With the spark the light may be considered as originating mainly in the hot central "core" of the spark, and that in passing through the less heated vapors enveloping it certain wave-lengths are absorbed, giving rise to the absorption lines, just as in the case of the arc.⁵ With the direct-current arc, however, we have an invariable source of light whose spectrum is the same from instant to instant, but with the spark I believe this is far from true.⁶ The light pro-

¹ Lippich, *Pogg. Ann.*, 137, 465, 1870; Lord Rayleigh, *loc. cit.*; Michelson, *loc. cit.*, p. 238.

² A. Schuster *Astrophysical Journal*, 3, 292, 1896.

³ A. A. Michelson, *loc. cit.*

⁴ *Loc. cit.*

⁵ Jewell, *loc. cit.*, p. 239.

⁶ Schuster and Hemsalech, *Phil. Trans.*, 193A, 189, 1900.

duced during the first oscillations of a group must pass through less cooler vapor than that produced by the later ones after the vapors have had time to accumulate;¹ and should therefore give narrower absorption lines, and also tend more to give bright lines. The spectrum obtained is then a composite of an infinite number of superposed spectra, giving varying degrees of reversal, and for some lines perhaps even superposing the bright line and the reversed line. The latter would account for the fogging of the reversed lines (on the negative) which makes determination of shift so difficult, and also would account in part for the failure of certain lines to reverse which do reverse in the arc. That the first oscillations of a group produce narrower reversals is proven, I believe, by No. 63*a*, for which a large non-inductive resistance was used to damp² the oscillations and cut out the later ones. To be sure, the energy of the spark is simultaneously decreased with increase of resistance, which also tends to narrow the lines.

According to the preceding hypotheses, it follows that the width of the metallic absorption lines should increase with the density of the metallic vapors, whether this density is produced by the pressure of the surrounding gas, by rapidity of evolution of vapor, or by both. The thickness of the absorbing layer—or, in other words, the amount of vapor—is important as regards absorption lines, which are the only lines present in many cases. I shall therefore limit myself to showing how increase of pressure, capacity, etc., influences the amount and density of the vapor.

Clearly the amount of vapor about the spark depends not only upon its rate of production, but also upon its rate of dissipation.

¹ H. Crew has recently shown that the alternating arc in different phases produces different spectra.

² From the logarithmic decrement, the relative charge on the condenser at the n th oscillation compared to the first is tabulated (Table IV) for various resistances up to 76 ohms. The capacity, inductance and some of the resistances are the same practically as those used for No. 63. It will be seen that with only 10 ohms, less than half (0.44) of the charge is left on the condenser after one complete period, although 76 ohms is necessary to make the discharge aperiodic. The table shows that the very similar spectra, No. 63*a* and No. 63*b*, must have been produced almost entirely by the first oscillation; and No. 63*c*, by the first five or six oscillations; because 16.9 ohms was used with No. 63*b*, and the table shows that after one full period but 0.25 of the charge remains, after four periods but 0.063.

TABLE IV

RELATIVE CHARGE ON THE CONDENSER AT THE n TH VIBRATION(Inductance and capacity the same as used for No. 63. Period = 7×10^{-6} .)

Resistance	When $t = \frac{T}{n}$	$t = \frac{2T}{n}$	$t = \frac{nT}{2}$
76.0 ohms	0.000		
50.0 ohms	.004	0.000016	
16.9 ohms	.25	.063	
10.0 ohms	.44	.194	
5.0 ohms	.67	.45	$n = 8$ 0.002
1.0 ohms	.92	.846	$n = 16$ 0.5
0.1 ohms	.993	.986	$n = 160$ 0.5

The former increases with the energy; the latter increases with the temperature, with the spark-length, and with *decrease* of pressure (increase of free path). Increase of the energy in the spark through increase of the energy of the primary circuit should, then, increase the width of the reversed lines. Increase of capacity causes a greater amount of electricity to surge through the spark at each oscillation, thus developing more energy and more vapor, and consequently producing wider lines. The increase of energy in the former case is probably brought about mainly through causing more groups of oscillations to occur during each cycle (see footnote 2, p. 231), with but little change in the energy of each group. It is also probable that vapor formed by one group of oscillations is pretty well dissipated before the next group (about $1/1000$ sec. later) occurs, while with increase of capacity the increase in energy comes with each group and each oscillation. This difference accounts for the fact that capacity change affects the spectrum more than (direct) energy change does (p. 237).

Increase of pressure not only increases the energy, but also decreases the free path. At the same time, the spark-gap must be made much shorter (p. 226); so that the vapors are more confined and hence the light from the "core" must pass through a much thicker stratum, as may be seen by comparing *A* and *B*, Fig. 8. For these reasons, pressure is the most important variable in affecting the spectrum.

Since increase of inductance (L) increases the period ($T = 2\pi\sqrt{LC}$), it will be seen that this decreases the current, as the oscillating charge is the same, and hence decreases the energy; and narrower lines should result, as found. As the spark-gap must be lengthened to increase the potential-drop over the spark, the

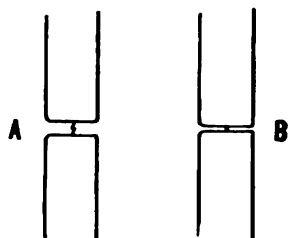


FIG. 8

escape of the vapor is thereby facilitated (see Fig. 8) so that narrower lines result with increase of potential, as shown in No. 71. On the other hand, increase of potential causes an increase in the charge, and hence in the energy, and therefore might be expected to produce wider lines. Under some conditions I think this might occur, but I have not observed it.

The effect of the nature of the gas, duration of exposure, and oscillation period have already been discussed on pages 237, 238, and 242, respectively. The actual value of the current during oscillation is too uncertain, and its effect is also too intimately connected with that of energy, to warrant, or require, separate discussion, further than given on pp. 232 and 243.

SHIFTS OF SPECTRAL LINES

Humphreys and Mohler¹ showed that if the gas surrounding the arc is subjected to several atmospheres pressure, the arc lines are slightly displaced relatively to those of the arc at atmospheric pressure.

This displacement, or shift, was determined by them for several lines of nearly all the metals. Since then several investigators² have studied the shift of the spectral lines of the spark in compressed gases. Of these Hale and Kent used the highest pressures (1 to 53 atmospheres) and found, for some of the iron lines, shifts as high as 0.22 tenth-meters.

Whether other causes than pressure may produce shift in the case of the spark spectrum is a much-mooted question. Eder and

¹ *Loc. cit.*

² J. F. Mohler, *Astrophysical Journal*, 10, 202, 1899; Hale and Kent, *ibid.*, 17, 154, 1903; and others.

Valenta¹ found no such shifts, while Kent² and others have found them. Kent has recently repeated his work with great care and is satisfied that such shifts exist. In general, previous investigations have shown that shift increases with increase of capacity and decreases with increase of inductance.³

The shifts of about thirty lines have been determined from No. 187, which has fairly well-defined reversed lines, to see if any grouping of lines could be made upon the basis of equal shifts. The shifts of a few lines at pressures of 80 and 100 atmospheres have also been measured.

Measurement of shift.—The shift of the lines of the spark spectrum with reference to those of the arc comparison spectrum taken on the same negative was measured with the dividing engine, upon which was mounted a low-power microscope.

In lieu of cross-hairs, a system of fine lines ruled on glass, as shown in Fig. 9, was finally used. The adjustment was so made that some one of these lines was near one edge of the spectral line, while some other one was equally distant from the other edge. By this means more accurate settings could be made than with a single cross-hair, set on the

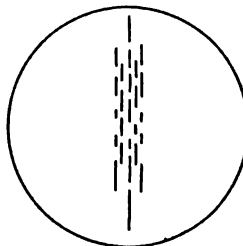


FIG. 9.—Reticle of microscope.

middle. A broken line is far superior to a continuous line, as it permits a nearly unobstructed view of the edge of the spectral line, which is essential with lines that shade off so gradually in intensity.

RESULTS

In Table V the shift and width of thirty lines of No. 187 and No. 186 (see Table II) are given, together with shifts obtained by Hale and Kent⁴ for some of the same lines at about the same pressure and in the same gas (CO_2 , 53 atmospheres). In column 4 r and v refer to the relative widths of the red and violet components of the bright line on each side of the reversal, r (red) being toward the longer wave-lengths. It will be seen that there is but one exception to the rule that the red component has the greater width. This

¹ *Astrophysical Journal*, 19, 251, 1904.

² *Loc. cit.*, p. 221.

³ Hale and Kent, *loc. cit.*, p. 221.

⁴ *Loc. cit.*, p. 221.

is due partly to shift and partly to unsymmetrical widening of the bright line. In all cases the shift refers to the reversed (i. e., absorp-

TABLE V

WAVE-LENGTH OF LINE	WIDTH IN TENTH-METERS			SHIFT									
	Emission Line	Absorption Line	r* and v*	For Plate No. 187 Determinations						Hale and Kent	Humphreys and Mohler	For Plate No. 186	
				I	II	III	IV	V	Average			Shift	Width of Absorption Line
$\lambda 3687.62$	0.53	0.03	$r=1$ $v=1$	0.089	0.121	0.138	0.116	0.071	0.107			0.123	0.20
$\lambda 3709.37$	0.67	.11	$r=3$ $v=2$	.126	.112	.133	.106		.119				
$\lambda 3722.71$	0.47	.13	$r=4$ $v=1$	.064	.035								
$\epsilon 3733.47$		.09		.04	.040		.040						
$\epsilon 3758.38$	1.33	.212	$r=3$ $v=2$	.094	.076	.093	.082	.102	.089			.127	.60
$d 3763.94$	0.93	.13	$r=2$ $v=1$	.084	.064	.085	.085	.093	.082			.135	.35
$h 3765.71$	.27	0		.095	.090	.116	.102	.080	.097	0.12		.180	.18
$\epsilon 3767.33$	.80	.08		.118	.104	.108	.111	.133	.115			.143	.25
3805.49	.27	0		.076	.093		.058	.061	.068				
$h 3813.17$	.27	0			.076	.065	.089	.065	.074			.110	.20
$\epsilon 3815.99$	1.20	.13	$r=2$ $v=1$	.091	.109	.112	.102	.093	.104	.14		.158	.35
$\epsilon 3824.63$	0.66	.13	$r=2$ $v=1$	.058	.53	.054	.038	.055	.052				
$\epsilon 3827.97$	1.10	.13	$r=3$ $v=2$	.100	.121	.136	.129		.126	.20		.175	.22
$d 3834.42$	1.00	.16	$r=3$ $v=2$	.092	.096	.90	.105	.092	.095			.149	.32
$\epsilon 3856.52$	0.66	.08	$r=3$ $v=2$	.043	.052	.053	.066	.061	.055			.085	.25
$h 3865.70$		0		.076	.064	.081	.093	.060	.075			.160	.23
$g 3969.39$	.50	0		.110	.080		.085		.092			.149	.26
$h 3977.91$	.22	0				.082	.090	.054	.075				.24
$h 3997.55$	.27	0				.081	.085	0.71	.079		0.129		.22
$h 4022.02$	.20	0		.077	.090	.085	.097	.118	.093			.180	.64
$h 4030.89$	.22	0					.106						
$h 4033.22$	.18	0				.074	.077		.075				
$\epsilon 4045.98$	1.60?	.18	$r=3$ $v=2$			.104	.113	.102	.106		.089	.170	.40
$\epsilon 4063.75$	1.	.1		.100	.118	.112		.090	.105	.18	.102		
$\epsilon 4071.90$	0.9	?			.128	.134			.131				
$h 4118.72$	.27	0				.106							
$h 4132.20$				.103	.112				.107			.195	.22
$h 4156.93$	.20	0		.057	.087	.076		1.	.073				
$h 4199.26$	.70	0		.085	.094	.092		.088	.090		.120	.180	.20
$h 4219.52$	.27	0		.088	.114	.106		.079	.097		.085		

(* When a bright line has superposed upon it an absorption line, r and v , respectively, refer to the relative widths of the red and violet components of the bright line.

tion) line, excepting for those lines of No. 187 whose width of reversal (column 3) is marked zero.

Column 12 gives the calculated shift for the arc at 50 atmospheres, based upon shifts obtained by Humphreys and Mohler¹ at 10 or 12 atmospheres and upon a linear relationship between shift and pressure which they believe to exist. There is fairly good agreement between these calculated values and those determined by me with the spark at 50 atmospheres (column 10). The large capacity and inductance of No. 187 gives a frequency of only 3570, which is not vastly higher than sometimes used with the alternating arc, so that similar shifts might be expected (see p. 242).

It will be seen that the shift obtained by Hale and Kent (column 11) is uniformly larger than that of No. 187, and smaller than that of No. 186. When taking No. 186, a considerably larger capacity was used than that employed by Hale and Kent, which would account for the greater shift (due to unsymmetrical widening of lines); while No. 187, likewise with larger capacity, had also several thousand times as large inductance, which may account for the smaller shift (large inductance produces narrow lines, hence less of false shift due to unsymmetrical widening).

In Table VI the lines marked with a (+) are reversed. It will be seen that in No. 112*a* but two lines, $\lambda\lambda$ 3720.08 and 3737.28, are reversed; so that these may be termed the most easily reversed and are designated by *a* (column 1). Those reversed in No. 143*h* (the arc) and not in any others are designated by *g*. Those not reversed in the arc may be grouped as class *h*. It was thought that similar lines might be similarly shifted. In column 10, Table V, there are five lines with shifts from 0.073 to 0.075, which all belong to class *h*. To determine whether or not this accords to some law of shift of the lines of a series of Kayser and Runge, will require more experimental evidence than is at present available.

In Table VII are given shifts for some of the lines of plates Nos. 137, 44, 127, and 190, at pressures of 70, 80, 100, and 100 atmospheres, respectively. With No. 190, CO_2 was the gas used. At 100 atmospheres CO_2 is a liquid, in which it was found impossible to run the spark long enough to obtain a good spectrum. By heating

¹ *Loc. cit.*, p. 222.

TABLE VI

Wave- Length	Arc. No. 143 ^a	No. 112c	Arc. No. 143 ^a	No. 170e	No. 120b	No. 112b	No. 120c	No. 112e	Wave- Length	Arc. No. 143 ^a	No. 112c	No. 143 ^e	No. 170e	No. 120b	No. 112b	No. 120c	No. 112e
f3680.00	+	+							d3834.42	+	+	+	+	+			
f3687.62	+	+							e3841.20	+	+	+	+	+			
d3705.00	+	+	+		+				c3856.52	+	+	+	+	+	+		
g3709.37	+		+						b3859.50	+	+	+	+	+	+	+	
a3720.08	+	+	+	+	+	+	+	+	h3865.70								
f3722.71	+	+	+						d3878.15	+	+			+			
e3727.79	+	+		+					c3886.43	+	+	+	+	+	+		
e3733.47	+	+	+	+					f3899.85	+	+	+					
b3735.01	+	+	+	+	+	+	+		h3922.5		+						
a3737.28	+	+	+	+	+	+	+	+	g3969.39	+							
b3745.50	+	+	+	+	+	+	+		h3977.91								
c3748.41	+	+	+	+	+	+	+		h3997.55								
b3749.63	+	+	+	+	+	+	+		h4022.02								
c3758.38	+	+	+	+	+	+			h4030.89								
d3763.94	+	+	+	+	+				h4033.22								
h3765.71									c4045.98	+	+	+	+	+	+		
e3767.33	+	+	+	+					e4063.75	+	+	+	+				
h3813.17									e4071.90	+			+				
e3815.99	+	+	+	+					h4118.72								
b3820.50	+	+	+	+	+	+	+		h4132.20								
c3824.63	+	+	+	+	+	+			h4156.93								
c3826.02	+	+	+	+	+	+			h4199.26								
e3827.97	+			+					h4219.52								

the compression tube to 38°, which is well above the critical temperature for CO₂, a fairly good spectrum was finally obtained after about two weeks' work. Only a few of the lines on these negatives are well enough defined to permit of shift determinations, but they were the best obtainable at such high pressures.

The shifts on No. 190 are larger than those of No. 127, although both at 100 atmospheres. For No. 127 hydrogen was the gas used,

TABLE VII

A	PLATE No. 190		PLATE No. 127		PLATE No. 44		PLATE No. 137		PLATE No. 187	
	Shift	Width	Shift	Width	Shift	Width	Shift	Width	Shift	Width
3763.94...	0.231	0.75			0.131	0.40			0.082	0.13
3767.33...	.264	.80	.44	0.70	.150	.60			.115	.13
3856.52...			.116	.60	.109	.35	.088	.75	.055	.08
3969.39...	.292	.60								
4063.75...	.257	.65					.124	.50	.105	.1

Shift and Width are expressed in tenth-meters

and the shifts are about the same as those of No. 187 at 50 atmospheres in CO_2 . Probably as a result of greater shift of the emission line than of the superposed absorption line, the violet component of the emission line is sometimes wanting.¹ The following lines of No. 170b are of this class:

3977.89	4107.65
4009.86	4156.97
4014.68	4175.81
4022.02	4219.52

To account for shift, Schuster² has suggested that the light-emitting particle may have a period slightly greater than its free period because of the proximity of other particles of like period. Also, according to the electromagnetic theory of light, the atom may be viewed as an infinitesimal Hertz oscillator whose capacity will increase if the dielectric constant ϵ , of the surrounding medium is increased.³ An increase of ϵ may be brought about by increase of pressure as well as by changing from hydrogen⁴ ($\epsilon=1.000264$) to CO_2 ($\epsilon=1.000946$); for if

$$\begin{aligned}\epsilon &= 1 + a, \\ \epsilon_1 &= 1 + Pa, \\ &= 1 + P(\epsilon - 1),\end{aligned}$$

where ϵ and ϵ_1 are the dielectric constants of a gas at one, and at p atmospheres pressures, respectively. Calculating upon this basis and from $T=2\pi\sqrt{LC}$, the shift of the lines of No. 127 (100 atmospheres pressure) for $\lambda 4000$ should be about 72 tenth-meters. The observed shifts are only about 0.15 tenth-meters.

If, however, we postulate a certain region B about the atom into which no other atoms can enter, we thus preclude variation of ϵ in just that region whose ϵ most affects the capacity of the atom. This might account for the above great discrepancy between the observed and the calculated shifts. A metal for which B is large would give correspondingly small shifts. My results point to greater shifts with the gas of greater ϵ , namely CO_2 ; still it seems that in the dense metallic vapors in the spark, few CO_2 atoms will

¹ Hale and Kent, *loc. cit.*, p. 221.

² *Astrophysical Journal*, 3, 292, 1896.

³ *Ibid.*, 5, 210, 1897.

⁴ L. Boltzmann, *Pogg. Ann.*, 155, 403, 1875.

minge, so that the value of ϵ_1 will depend rather upon the proximity of neighboring metallic atoms.

In applying what we know of finite condensers to a supposed one of atomic dimensions, we verge on the purely speculative. This theory, however, may yet be shown to be quite tenable.

SUMMARY

It has been shown that the lines become wider with increase of capacity,¹ pressure,² and energy, and narrower with increase of inductance,¹ resistance, voltage, and time of exposure. The probable cause of widening in all cases is an increased amount of vapor about the spark, which depends upon the rate of production of the vapor (which in turn depends upon the watts expended in the spark during oscillations), and upon its rate of dissipation. When CO_2 is used in the compression chamber, wider lines are obtained than with air, but narrower than with hydrogen. Estimates of the probable value of the current, watts, potential-drop, and resistance of the spark during oscillations have been made, based upon the observed (average) values.

The shifts for thirty different lines have been determined and found to be about the same as those measured by Humphreys and Mohler (with the arc), if reduced to the same pressure. Shifts have been determined for pressures up to 100 atmospheres in CO_2 and hydrogen, the latter giving the smaller shifts.

In conclusion I wish to thank Professor Mendenhall for the interest he has taken in the work, and Professor Snow for placing at my disposal all the necessary material and apparatus. I also take great pleasure in acknowledging my indebtedness to Mr. H. W. Kircher, for faithful assistance and valuable suggestions during the early part of the work; and to Mr. R. J. Wallace, photophysicist at Yerkes Observatory, for numerous suggestions in preparing the positives for the photo-engraver.

PHYSICAL LABORATORY, UNIVERSITY OF WISCONSIN,
August 6, 1906.

¹ Hale and Kent, and others, had already observed these effects of capacity, pressure, and inductance, but with smaller values and through much smaller range.





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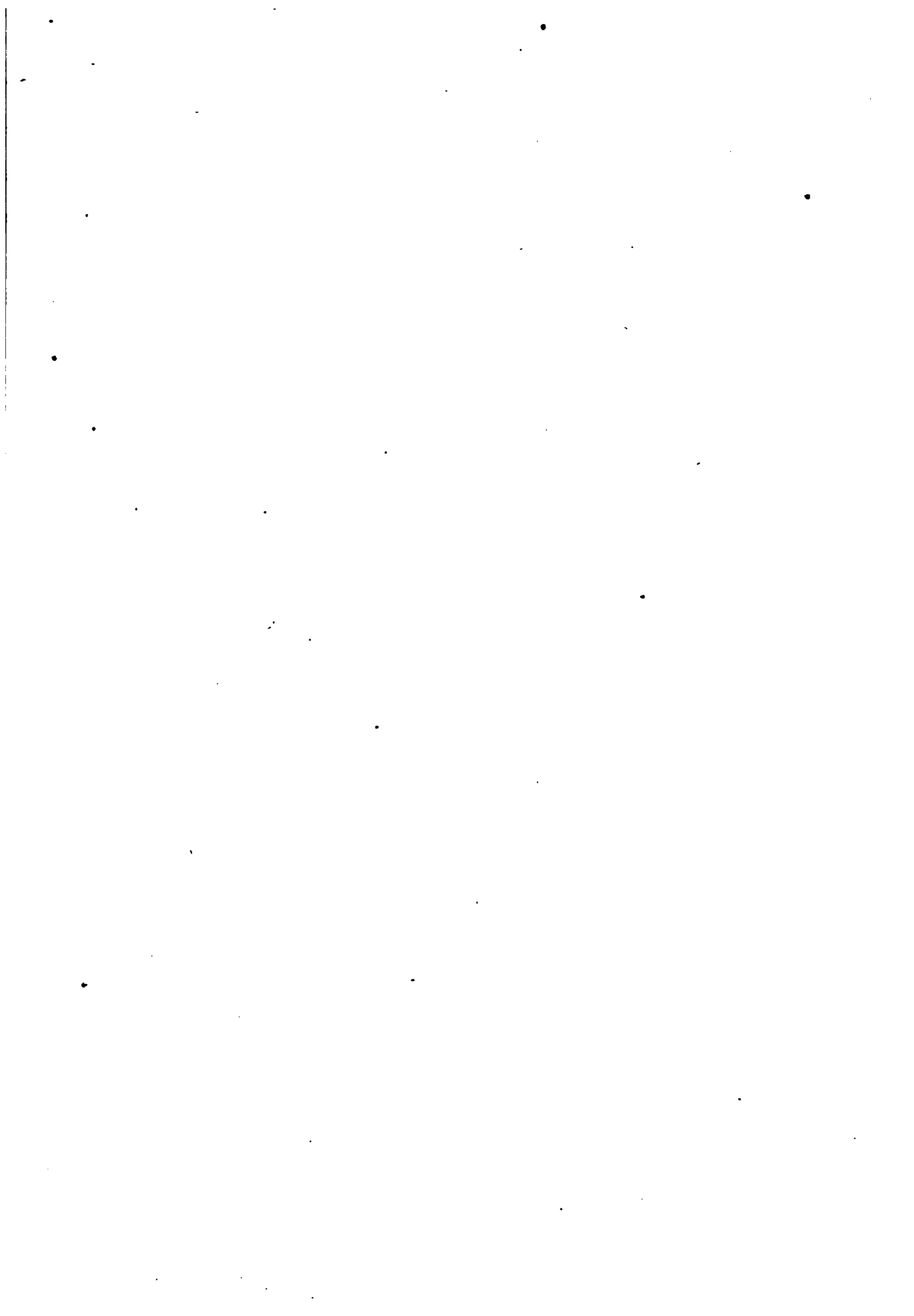
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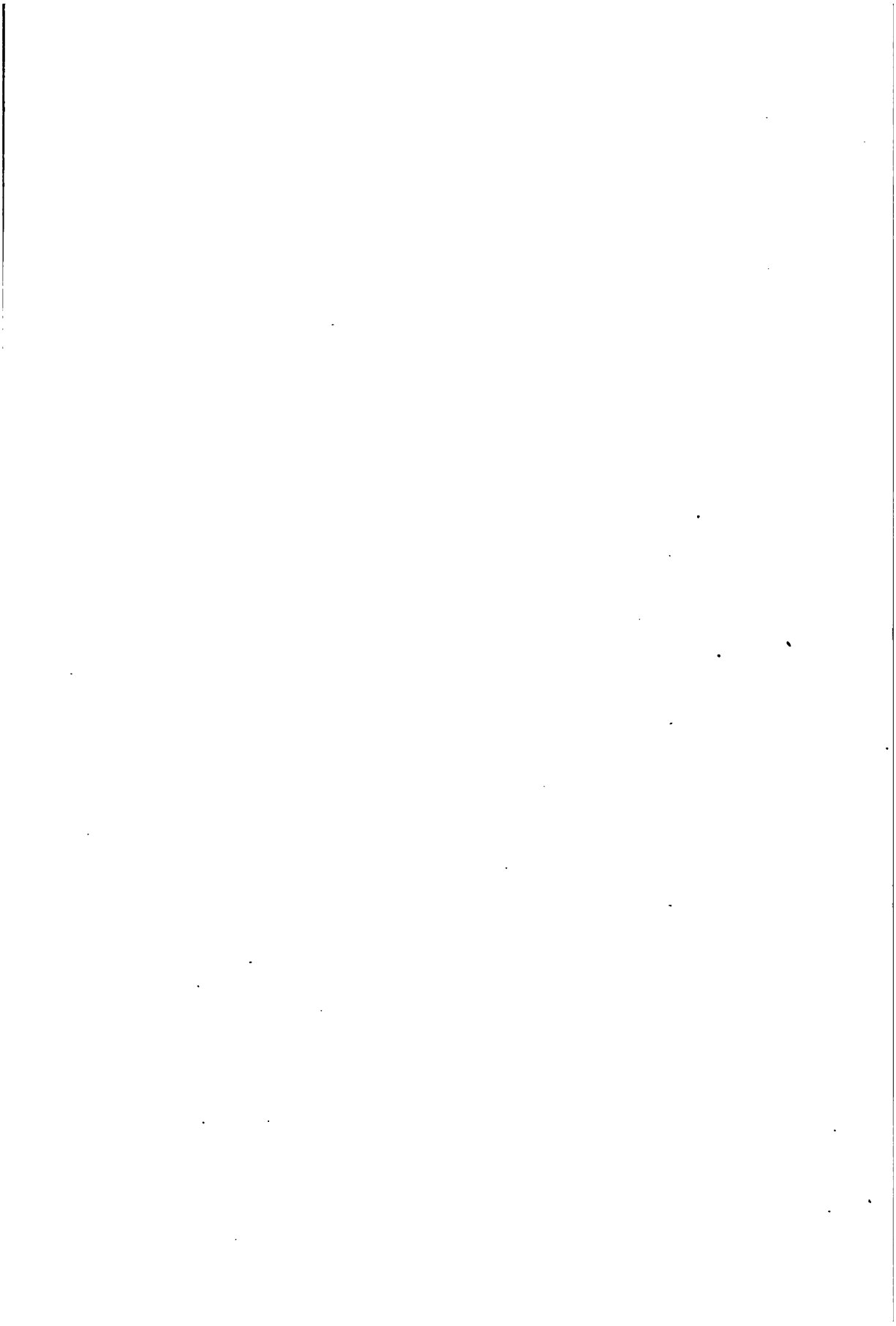
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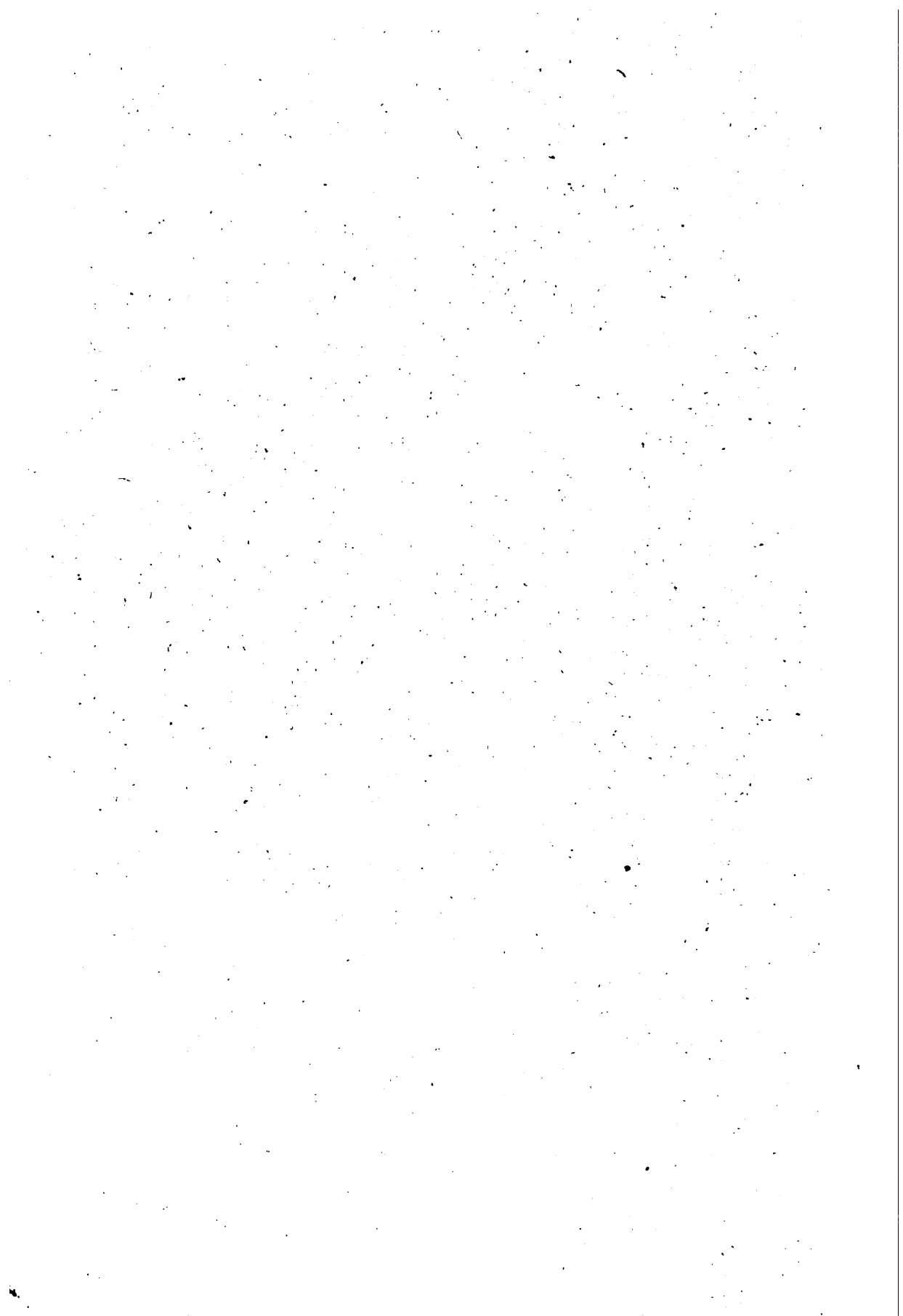
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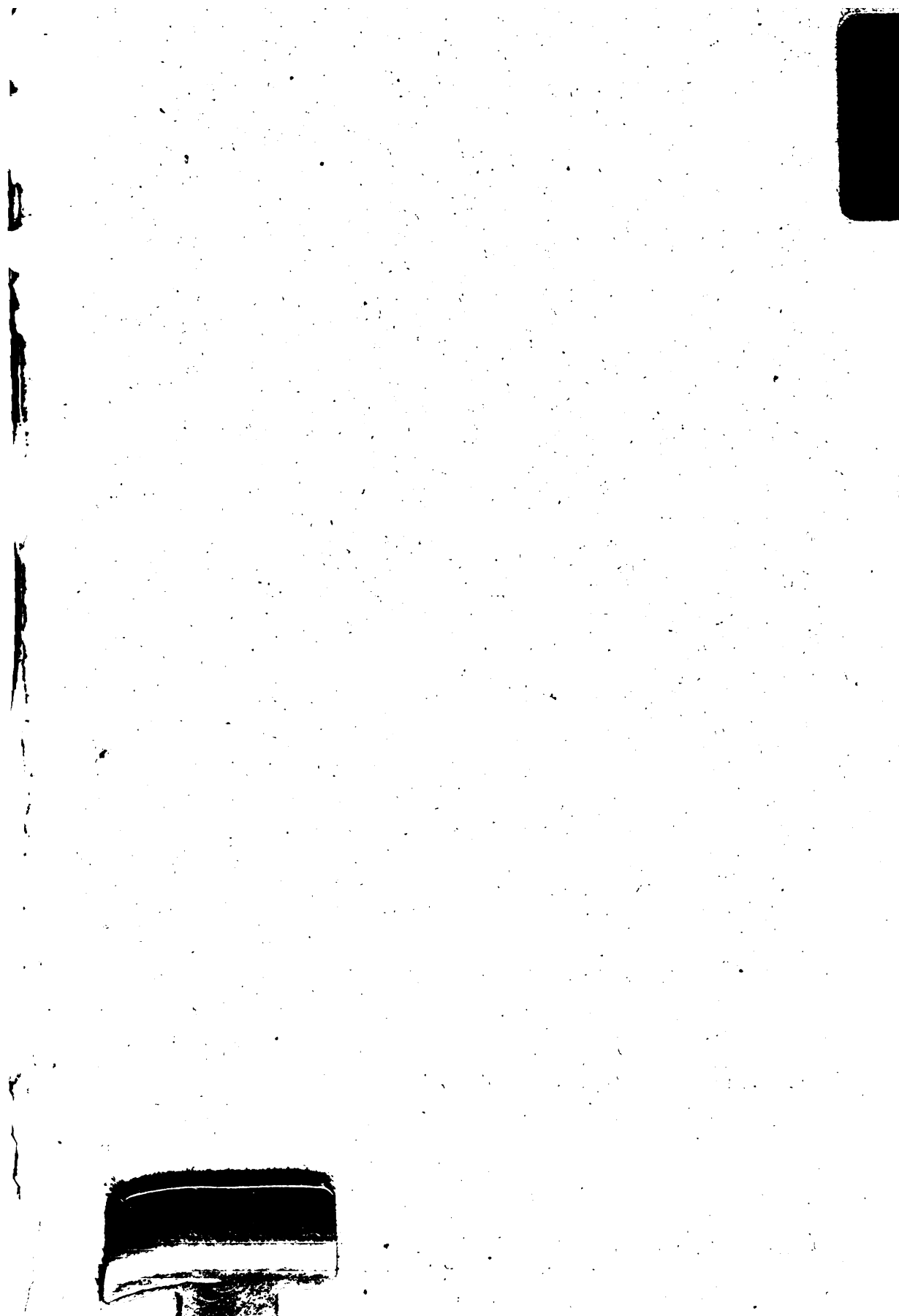




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